DEVELOPMENT OF AN ECO-FRIENDLY GRAIN DRYER BASED ON DESICCANT DEHUMIDIFICATION

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1. Introduction:

Agriculture plays a vital role in India's economy. Over 58 per cent of the rural households depend on agriculture as their principal means of livelihood. The Indian food industry is poised for huge growth, increasing its contribution to world food trade every year due to its immense potential for value addition, particularly within the food processing industry. The Indian food and grocery market is the world's sixth largest, with retail contributing 70 per cent of the sales. The Indian food processing industry accounts for 32 per cent of the country's total food market, one of the largest industries in India and is ranked fifth in terms of production, consumption, export and expected growth.

Poor condition of Indian farmer is due to the lack of means for agriculture techniques available to him. Large volumes of grains are produced by Indian farmers but due to lack of drying and storage capabilities, farmers do not get proper benefits. If a low cost and efficient grain dryer is available, the farmer can afford long term storage after processing the grain and hence can get the proper market value of his product.

Traditionally, Indian farmers use sun drying for various grains which is dependent on climatic conditions. Today, the solar energy technologies are getting phenomenal growth. Solar radiation is direct source for producing heat. It constitutes the most abundant and best renewable energy resources. Solar energy does not create global warming, because it is one of the cleanest energy resources. It does not cause CO2 or other gaseous emission into the air.

Drying of food grains uses solar energy. The moisture content in fresh agricultural products is the basic cause for spoilage. The removal of moisture prevents growth and reproduction of microorganisms and it minimizes moisture deteriorative reactions [1]. If water is removed then the shelf life of agricultural product can be increased. It also reduces the cost of storage and transportation by reducing both weight and volume of final product. The quality of dehydrated food product is influenced by drying conditions such as temperature, relative humidity [2]. Now a day's various type of drying technologies is used for drying. Sun drying is traditional method of preservation of grains. The quality of sun dried product is poor with regards to its colour and flavour due to direct exposure to sun [3]. Also, sun drying is not hygienic, does not have a control over drying and is not dependable throughout the year. In general drying is accomplished by thermal techniques and thus involves the application of heat, most commonly by

convection currents of air. Throughout the convective drying of solid materials, two processes occur simultaneously namely, transfer of energy from the local environment in the dryer and transfer of moisture from within the solid. Therefore this drying may be considered as simultaneous heat and mass transfer operation. During drying of grains, agent/medium used is atmospheric air which contains the moisture in accordance with the atmospheric humid conditions.Use of the proper drying conditions can reduce drying time and improve product quality. However, hot air can be used for drying it rarely fails to preserve product quality, because in drying operation the product is exposed to the drying environment for a long period [4]. Although sun drying consumes no energy, the absence of control over drying temperature was actually felt in open sun drying and the passive solar dryer, and then the later research tended to have a preference to the use of forced air circulation solar dryer. Most of the designs of forced convection solar dryers have recently been proposed for drying applications in more countries [5]. A simple effective solar drier based on desiccant drying will use solar radiation as heat requirement for charging the desiccant material. It will be simple in use, effective in performance and eco-friendly using solar energy as heating source.

1.1 Drying

During harvesting food grains contain large amount of moisture. The moisture content also depends on the type of grain and the season of its harvesting. These are the target moisture content for each of the key postproduction operation shows in Table (1)[6]

Table-1: Moisture contents

Operation	**Desired moisture content**	**Primary losses**
Harvesting	20–25%	shattering if grain is too dry unfilled and many green grains if too wet.
Threshing	20–25% for mechanical threshing less than 20% for hand threshing	incomplete threshing, grain damage, cracking/breakage.
Drying	final moisture content is 14% or lower	spoilage, fungal damage, discoloration
Storage	less than 14% for grain storage, less than 12% for seed storage less than 9% for long term seed preservation	fungal, insect, and rat damage
Milling	13–14%	grain cracking and breakage over milling

Grains should be dried to certain moisture content (MC) depending on storage period to avoid potential problems. A good maximum storage temperature is about 18 °C. The following table (2) shows some of these problems and their remedy by safe storage.

Table-2: Moisture content for safe storage

Storage period	**Required MC for safe storage**	**Potential problems**
weeks to a few months	14% or less	molds, discoloration, respiration loss insect damage, moisture adsorption
8–12 months	13% or less	insect damage
storage of farmer's seeds	12% or less	loss of germination
<1 year	9% or less	loss of germination

Drying equipment is classified in different ways, according to following design and operating features. It can be classified based on mode of operation such as batch or continuous, In case of batch dryer the material is loaded in the drying equipment and drying proceeds for a given period of time, whereas, in case of continuous mode the material is continuously added to the dryer and dried material continuously removed. In some cases vacuum may be used to reduce the drying temperature. Some dryers can handle almost any kind of material, whereas others are severely limited in the style of feed they can accept. Drying processes can also be categorized according to the physical state of the feed such as wet solid, liquid, and slurry. Type of heating system i.e. conduction, convection, radiation is another way of categorizing the drying process. Heat may be supplied by direct contact with hot air at atmospheric pressure, and the water vaporized is removed by the air flowing. Heat may also be supplied indirectly through the wall of the dryer from a hot gas flowing outside the wall or by radiation. Dryers exposing the solids to a hot surface with which the solid is in contact are called adiabatic or direct dryers, while when heat is transferred from an external medium it is known as non-adiabatic or indirect dryers. Dryers heated by dielectric, radiant or microwave energy are also non adiabatic. Some units combine adiabatic and non adiabatic drying; they are known as direct-indirect dryers. To reduce heat losses most of the commercial dryers are insulated and hot air is recirculate to save energy. Now many designs have energy-saving devices, which recover heat from the exhaust air or automatically control the air humidity. Computer control of dryers in sophisticated driers also results in important savings in energy. In all the above dryers, drying agent/medium is atmospheric air which contains the moisture in accordance with the atmospheric humid conditions.

2. Grain dryers and drying processes

Drying equipment is classified in different ways, according to the design and operating features. The process can be carried out in three ways using heat transfer phenomenon, namely, (a) Drying of wet solids- convective drying e.g. - tray dryer, tunnel dryer, rotary drum dryer, (b) conductive drying- vacuum dryer, and (c) radiation drying- microwave dryer. The figure (2.1) shows the working of a Tray Dryer.

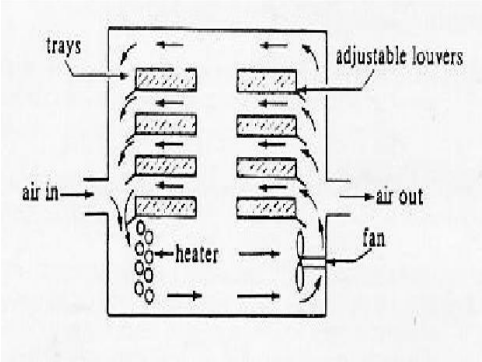

Fig.2.1.Tray dryer

The tray dryer consists of double layer stainless steel chamber, insulation between the layers. Inside layer is mirror polished. It contains a heating device, thermostat. Wet solid (grain) is placed into stainless steel tray .Trays are placed in the shelf of drying chamber. Fresh air enters an inlet, which passes through a filter a heater a fan. The hot air is circulated by means of a few fans usually at 2 to 5 m/s air velocity. As water evaporates from the surface of the solid the inside water diffuses from the interior of solid by capillary action, moist air is partially removed through a filter and outlet. Only 10-20% fresh air introduced. Thus constant temp and uniform airflow over the material can be maintained for achieving uniform dryers.

In Fluidized bed dryer's air velocity is greater (1.5-7.5m/s) which makes the wet granules to dry quickly. Time for drying is about 40 minutes. Thermal efficiency is 2 to 6 times than tray dryer.

2.1 Desiccant based drying system

The potential capacity of both liquid and solid desiccants are high to absorb moisture and used in small or large scale drying for food product[7] Low-temperature desiccant based drying allows foods such as grains to be dried without losing the original color and texture. The system consists of an airflow control system to improve drying rate and temperature control at minimum damage to the food during the drying process in comparison with sun drying. For experimental evaluation, it is demonstrated that dried vegetables produced by this method retain their fresh color and high vitamin content [8]. However, the use of heat to evaporate moisture from the food also results in a loss of

fresh color, vitamins and texture. With the use of desiccant, the fresh color of food can be maintained if drying can be performed at low temperature [9]. In drying, desiccant is used to lower the air humidity and produce optimum air conditions required for drying irrespective of the ambient air conditions. Once the solid desiccants become saturated, they can be regenerated and used again [10]. The figure (2.2) shows Desiccant dehumidifier.

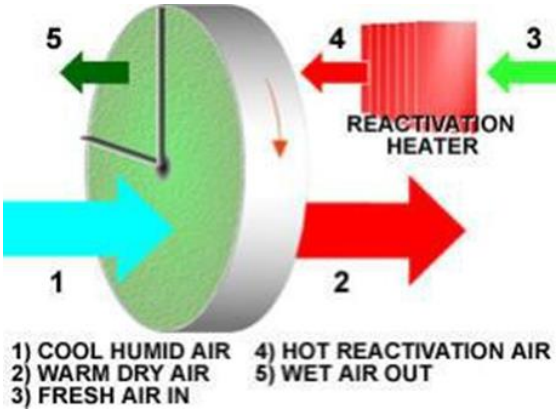

Fig.2.2. Desiccant dehumidifier

Reducing the relative humidity of hot air is a approach, which increases the moisture-absorbing capacity of drying air. The desiccant based drying system can be used for drying grains and reduce drying time and improve quality of grains. So, to solve the problem of uncontrolled drying temperature and unfavourable climatic conditions there is a need to develop a desiccant based grain drying system in which a dehumidifier is used to absorb the moisture from air and with the help of heater, air is dried to desirable relative humidity and temperature and passed through food grains kept in drying chamber. Temperature of drying air and airflow rate are crucial parameters for increasing the drying rate and dried grain quality and hence needs to be optimized for drying of grains in a desiccant based drying system.

2.2 Comparison between electrical dryer and desiccant based grain dryer

On comparing the drying process through desiccant system and other available system, it is observed that in a dryer, drying agent/medium is atmospheric air which contains the moisture in accordance with the atmospheric humid conditions. Drying air which passes through desiccant medium has low moisture content and is very efficient in drying the grains at a faster rate. Air passing through desiccant may contain humidity about 10% RH only and 60 to 70°C temperature which are more suitable for drying than

the air containing high RH around 70-90% RH.

Comparison may be also carried out on the basis of Grain Quality achieved through electrical drying and desiccant drying as desiccant drying involves drying through dehumidified and hot air. Energy consumption in the two processes may also be compare since the time taken in the drying process using desiccant will be lesser for same temperature. Another comparison may be carried out on the overall cost of drying the grains which includes equipment cost and running cost.

Keeping in view the above facts, the present study has been undertaken with the following objectives:

1) Evaluation of a desiccant dehumidifier for grain drying.
2) Design and development of desiccant based grain dryer
3) A detailed chart will be prepared, depicting the drying procedure for desiccant based drying system.

3. Grain moisture

In India, the production rate of grain are increased rapidly, due to advancement in production technologies, but due to storage problem, result in high losses in grain. Grain is small, hard, dry seeds, harvested for human being. The commercial grain crops are cereals such as wheat and rye, and legumes such as beans and soybeans. The quality of grain is depending in its moisture content. Higher the moisture content, the probability of spoilage is more. Table-3 shows the maximum moisture content levels at which cereal, pulse, can be sold as straight grade, as permitted under the Canada Grain Act [11].The moisture content levels exceed the values shown in Table 3, a penalty is charged.

Table-3: Maximum moisture content levels for straight grade seed (percentage wet weight basis)

Corn/maize	15.5
Oats	13.5
Rye	14.0
Soybean	14.0
Wheat	14.5

3.1 Moisture migration

At the time grain is first stored, grain moisture content is fairly uniform throughout the bin. With time, localized high moisture zones may develop due to changes in outdoor air temperatures. The low outside temperature cools the wheat nearer the wall. This results in a downward air flow through the grain and upward towards the centre of the bin. As the air moves through the grain it becomes warmer and begins to pick up moisture from the grain. Condensation occurs when the warm moist air hits the cool surface of the grain near the centre of the bin, thus leading to grain spoilage.

3.2 Theories of movement of moisture within the solids

Drying occurs in a substance due to surface evaporation of the moisture for surface evaporation to continue there should be movement of moisture from the depth of the solid to the surface. The nature of the movement of moisture influences the constant rate and falling rate periods.

Diffusion: Diffusion of moisture from the depth of the solids to the surface takes place because of concentration gradients. The concentration of moisture is more in the depth of the solids but less on the surface. During constant rate period the concentration of moisture at the surface is reduced but remains high in the depth of the solids. The high diffusivity of moisture allows the passage of moisture to the surface of the substance as fast as it can be evaporated. Thus the drying remains constant.

After this unsaturated surface evaporation starts dry spots appear on the solid surface and the surface reaches equilibrium moisture content of the gas passing over it. This is falling rate period

Capillary movement: In drying of substances the moisture moves to the surface through capillaries. The capillaries extended from the surface of the solid to the reservoir of moisture moves sufficiently enough to the surface to maintain a constant rate of evaporation. Thus the rate of drying remains constant.

After this unsaturated surface drying begins. The liquid surface comes down into the capillaries. Evaporation of moisture occurs below the surface of the solid and the diffusion of the vapour takes place from the depth of the solid to the surface

Vapour diffusion: This occurs when heat is supplied to one surface of the solid while drying proceed from another surface. The moisture evaporates below the surface of the solid diffuse out as vapour

Pressure diffusion: when a solid is dried the outside layer shrink. This shrinkage of the solid squeezes the moisture out to the surface.

Absolute humidity is the measure of water vapor (moisture) in the air, regardless of temperature. It is expressed as grams of moisture per cubic meter of air (g/m3).

Relative humidity also measures water vapor but relative to the temperature of the air. It is expressed as the amount of water vapor in the air as a percentage of the total amount that could be held at its current temperature.

Absolute vs. Relative moisture contents

Absolute moisture contents W_b is defined with the following formula:

$$W_b = \frac{m_w - m_s}{m_s} \times 100\ \%$$

where: m_w – weight of a sample before drying, m_s weight of a completely dry sample

Relative moisture contents W_w is defined with the following formula:

$$W_w = \frac{m_w - m_s}{m_w} \times 100\ \%$$

where: m_w – weight of a sample before drying, m_s weight of a completely dry sample.

Therefore the relationship between absolute and relative moisture contents is:

$$w_b = \frac{w_w}{1 - w_w}$$

$$w_w = \frac{w_b}{1 + w_b}$$

4. **Literature Survey:**

A desiccant Material is a material that naturally attracts moisture from both gases and liquids. There are various types of desiccant available, but all dehumidifier's uses as Silica Gel as the desiccant within the drying wheels. Silica gel is not a "gel" as the name implies, but in fact a porous granular form of silica which is made from sodium silicate. The internal structure of each silica granule is made up of a network of interconnecting microscopic pores, which by a process called physical adsorption or capillary condensation, attract and holds moisture within each granule. This trapped moisture can then, with the addition of heat, be released from the desiccant. This desiccant can then be used again and again.

A desiccant wheel is basically a circular plastic or styrene disk with an extended surface that is impregnated with silica gel. Commercially available desiccants include silica gel, activated alumina, natural and synthetic zeolites, titanium silicate, lithium chloride, and synthetic polymers. Fig.4.1. shows types of desiccant system.

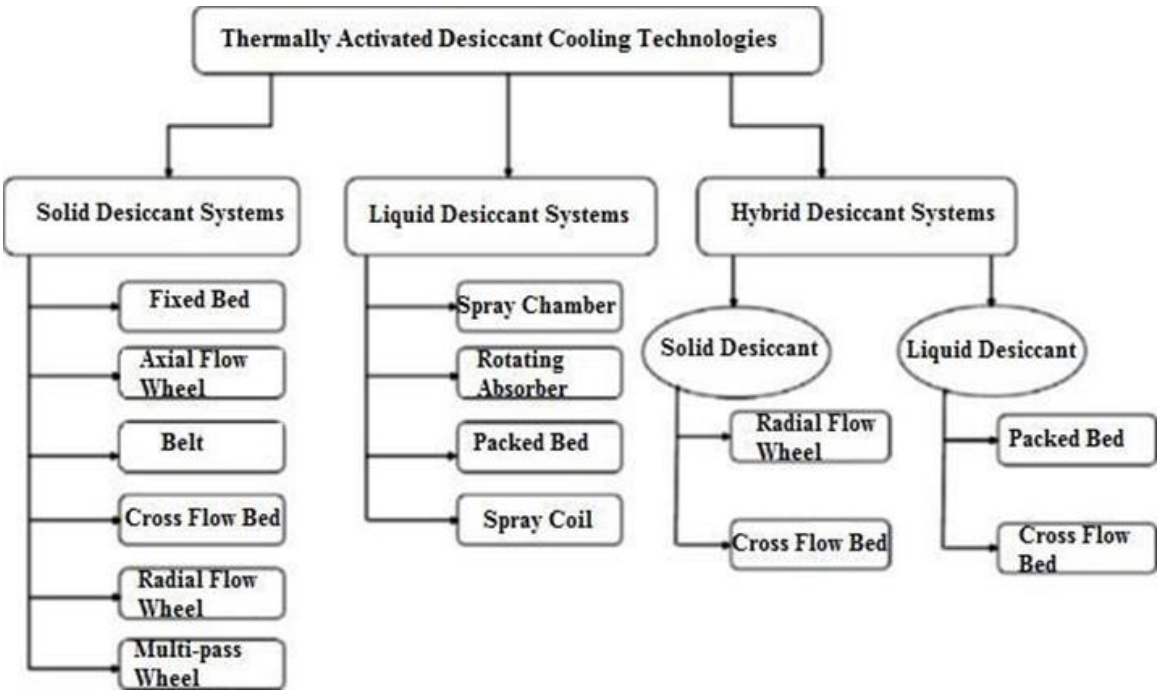

Fig.4.1. Types of Desiccant system

A detailed study of the research papers, books, reports etc. available in this area has been carried out. The different frameworks under which the literature survey has been performed are given below:

- Desiccant dehumidification system
- Drying system for grains

The important papers and their contributions belonging to each framework are discussed below one by one.

4.1 Desiccant dehumidification system

Desiccant systems can produce low temperature drying at a controlled rate which is very important for certain agricultural products. Desiccants can remove moisture from the air which, in turn, can be used for drying purposes. The weak desiccant can be regenerated by air under certain conditions so that the desiccant can be used continuously to remove moisture from air. The desiccants absorb (or release) moisture because of the difference in vapour pressure between the surface of the desiccant and the surrounding air. Solid desiccants are impregnated in a dehumidifier bed, usually a rotary disc which slowly rotates between the process and regeneration air streams. As the hot and humid process air passes through the desiccant wheel, the moisture is removed by the desiccant, and its temperature increases.

Miller reviewed the applications of combining solar energy and desiccant energy storage [6]. Desiccants are a potential media especially suited for drying applications. Both liquid and solid desiccants are manufactured and could be used in small or large scale drying for crop or food product drying.

Smith and Hwang developed a dehumidifier model which relates the outlet and inlet states of the dehumidifier [12]. The main energy input to such a system is primarily used for regenerating the desiccant. The necessary energy can be supplied by low-temperature heat sources for the regeneration, if the rotary dehumidifier matrix is properly constructed and appropriate selections are made for the type and amount of the desiccant. Ref. [13] tested the regeneration of a silica gel packed bed. The optimum operating time, after which the maximum amount of moisture had been removed, was determined at three regeneration temperatures, 65℃, 75℃ and 85℃.

Zheng investigated the effects of desiccant sorption properties, heat and mass transfer characteristics and size of the wheel on dehumidification performance [14]. They also discussed the isotherm shape of desiccant and it was found that to obtain maximum dehumidification, separation factor should be 0.07. Ref. [15] used the waste heat of a natural gas fired combined heat and power (CHP) system to regenerate a desiccant wheel which was used for the dehumidification of moist air in a swimming pool.

Dai and Wang discussed the effects of some important parameters, such as heat capacity, adsorption heat, rotational speed, regeneration temperature, thickness of the desiccant matrix and desiccant isotherm on the performance [16]. They also discussed the effect of some practical issues such as wheel purge, residual water in the desiccant and the wheel supporting structure on the wheel performance chart and discussed the effects of some important parameters, such as heat capacity, adsorption heat, rotational speed, regeneration temperature, thickness of the desiccant matrix and desiccant isotherm on the performance. The removal of moisture from foods retards many of the moisture-mediated deteriorative reactions and prevents the growth and reproduction of microorganisms [1]. The quality of dehydrated food product is influenced by drying conditions such as temperature, airflow, and relative humidity [2].

Author developed a desiccant rotary wheel coupled with a hot-air drying system and used to dry coarsely chopped coconut pieces [4]. Silica gel was selected as the desiccant material. However, energy consumption was higher, mainly due to the energy required for silica gel regeneration. The color of the dried coconut was affected by all drying conditions, but the most important parameter causing the product to become considerably darker was the relative humidity of the inlet drying air.

Catalano and Fucci proposed the system consists of humidity and temperature control during the food drying process by using a particular dehumidifier equipped with a desiccant rotor containing silica gel [17]. In each experiment the humidity, temperature and velocity of air is controlled and the moisture content and temperature as function of time is monitored.

Ref. [18] developed a one-dimensional transient heat and mass transfer equations for a desiccant wheel allowing lumped formulation. The performance model related the wheels design parameters (wheel dimension, channel size and desiccant properties) and operating parameters (rotary speed, condition of process and regeneration air and regeneration air flow). Several designs of forced convection solar dryers have recently been proposed for drying applications in developing countries [5].

Jeong [19] developed and analysed the concept of utilizing the exhaust heat (50℃) from fuel cell or air conditioning system as the heat source in a four partition desiccant dehumidification system which led to considerable saving of energy. Ref. [20] proposed that the air needed for regeneration was heated in an evacuated tube solar collector with a

surface area of 4.44 m2. The desiccants were regenerated at temperatures in the range of 54.3–68.3°C. Silica gel was observed to perform better at high as well as low flow rates for regeneration and adsorption than activated alumina and activated charcoal.

Ref. [21] have studied two different solar desiccant-dehumidification-regeneration systems have been studied. Both have the same glazed area and utilize similar mechanisms for dehumidification and regeneration. The solid desiccant used is silica gel and the particle sizes fall in the ranges of 6–8 and 2–4 mesh. The structures of the systems are simple and they are suitable for such applications as air-conditioning, drying, dehydration, and active cooling.

Misha and Mat.S [22] presents several works on the regenerative method of the desiccant system and its application in the drying system for both solid and liquid desiccant materials. Ref. [23] investigates different composite silica gel coated alumina sheets were first prepared and their texture properties, thermal conductivities and sorption characteristics were studied. Then a composite desiccant coated heat exchanger was developed and compared with silica gel coated one.

4.2 Drying system for grains:

Drying and dehydration are the removal of moisture from a given material. The Objective of drying is to remove water until the water activity is low enough to prevent growth of microorganisms. Drying of agricultural products is an important unit operation under post-Harvest phase. It is the process of removal of excess moisture from food products to a predetermined level. In order to reduce the amount of grain that is lost due to stress cracking, Medium temperature and slow cooling, or natural air and low temperature drying methods should be employed.

4.2.1 Drying Temperatures

Following factors as listed below are responsible for the maximum temperatures for drying cereal grain:

1. Length of storage
2. Low temperatures should be used if the grain is to be stored for 6 months or more.
3. Moisture content
4. The damper the grain, the longer the drying process. Low temperatures should be used.
5. Type of grain dryer

6. Lower temperatures should be used in dryers which do not mix or circulate the grain.
7. End use of the grain - malt or seed - low temperature.

Maximum safe air temperatures entering dryer for barley and wheat The excessive heat can damage cereal grain and reduce their ability to germinate, hence, maximum safe air temperatures must not be exceeded. The table (4) below shows the maximum safe temperature for various uses [11]

Table-4: Maximum safe air temperature

Grains	Seeding and malting	commercial	feed
Barley	45^{o}C	55^{o}C	80-100^{o}C
Wheat	60^{o}C	65^{o}C	80-100^{o}C

Mathematical equations

Using gibbs adsorption equation, Henderson developed the following equation to express the equilibrium moisture curve.

$$1 - RH = \exp[-cTM_{e^n}]$$

where, RH =equilibrium relative humidity, M_e=E.M.C dry basis percent , T= temperature ^{0}k and c and n = product constant varying with materials.

One approach to drying grain involves a high temperature, usually high speed, the grain is in batches or it is passed continuously through a container. The dryer is designed for optimum exposure of the grain to the drying air and for easy movement of the grain into and out of the drying chamber. Second approach to drying grain, referred to as low-temperature drying, takes place over an extended period while the grain is held in the storage bin.

Direct solar drying uses solar radiation to heat the material directly. It is a process used to preserve food, a natural convection drying process as the air movement is due to density differences. Indirect solar drying is a new technique, which involves some thermal energy collecting devices and dryers of special techniques. There exist several types of dryers size, the construction technique of which fulfil the special drying requirements of food products, many of which still operate rather based on experience than on scientific basis.

Madhlopa and jones [24] found that the dryer was suitable for preservation of mangoes and other fresh foods. Ref. [25] investigates the applicability of simplified

mathematical drying models from the research works proposed by several investigators to the drying of some agricultural products.

The investigation of the drying behaviour of different agricultural products has recently been carried out by several investigators, for example, green peppers [26], onions [27], red peppers [28-30], rough rice [31], bananas [32], mushrooms [33], potatoes [34], grapes [35] and pistachios [36].

Solar air heaters are simple devices to heat air by utilizing solar energy and employed in many applications requiring low to moderate temperature below 80°C, such as crop drying and space heating [37]. Drying processes play an important role in the preservation of agricultural products.

Bassey explained that the application of dryers in developing countries can reduce post-harvest losses and significantly contribute to the availability of food in these countries [38]. Estimations of these losses are generally cited to be of the order of 40% but they can, under very adverse conditions, be nearly as high as 80%. A significant percentage of these losses are related to improper and/or untimely drying of foodstuffs such as cereal grains, pulses, tubers, meat, fish, etc.

The author found that in sun drying, the crop is spread in a thin layer on the ground and exposed directly to solar radiation and other ambient conditions [39]. The rate of drying depends on various parameters such as solar radiation, ambient temperature,

wind velocity, relative humidity, and initial moisture content, type of crops, crop absorptivity and mass of product per unit exposed area.

The author of this paper visited a number of countries and studied the numerous designs available for solar drying in the region. Three types of solar dryers considered by the author as having the best potential for development in the Asia-Pacific Region are discussed. These are the natural convection cabinet-type solar dryer, the forced convection indirect solar dryer, and the greenhouse-type solar dryer [40]

Jayaraman and Das gupta studied quality characteristics of some vegetables dried by direct and indirect sun drying [41]. They observed that direct sun drying of vegetables was faster than drying inside solar cabinet. The physical properties of food products undergoing a combined sublimation and evaporation were studied [42]. Pieces of vegetables and potatoes were dried in a heat pump fluidized bed dryer at combined modes

with temperatures below the freezing point in the beginning and a final drying step at temperatures above the freezing point.

Kosuke and Ying [43] proposed the drying system consists of a desiccant-rotor dehumidifier, thermal transducers, linear potentiometers, fans, and a heater, with heating and air circulation control achieved using a feedback algorithm so as to maintain constant optimal temperature (49°C) and uniform drying rates within the drying chamber. The color of vegetables dried using the techniques was evaluated numerically using color-channel values 8 and was shown close to the color of fresh samples of cabbage, eggplant, carrot, butterbur and spinach. Spinach dried by this method also shown to retain a large proportion of the original vitamin C content, and good quality dried mushrooms can be obtained through the use of a slightly modified procedure. Drying by this system can be achieved up to 12 times faster than by sun drying, and up to 6 times faster than conventional desiccant-based drying.

Brenndorfer found that an improved technology in utilizing solar energy for drying grain is the use of solar dryers where the air is heated in a solar collector and then passed through beds of grain [44]. There are two basic types of solar dryer appropriate for use with grain: natural convection dryers where the air flow is induced by thermal gradients; and forced convection dryers wherein air is forced through a solar collector and the grain bed by a fan.

The drying process of rice normally require after harvesting. Most of the crop is dried at commercial drying installations or at rice mills in continuous-flow, heated-air dryers by the multi pass method. In California, commercial dryer use a combination system in which rice is dried to 16 to 18 per cent moisture in a continuous-flow, heated-air dryer, with ambient air drying finished while the rice is in storage.

A classification chart of drying equipment on the basis of heat transfer is shown in Fig4.2. This chart classifies dryers as direct or indirect, with subclasses of continuous operation.

Solar drying technologies are broadly classified in to three modes direct solar drying, indirect solar drying and mixed mode solar drying as shown in Fig 4.3. Solar dryer are the device used for product drying with proper application of solar energy. Solar dryers are classified by air movement in the drying chamber. It is generally classified according to natural circulation and forced circulation.

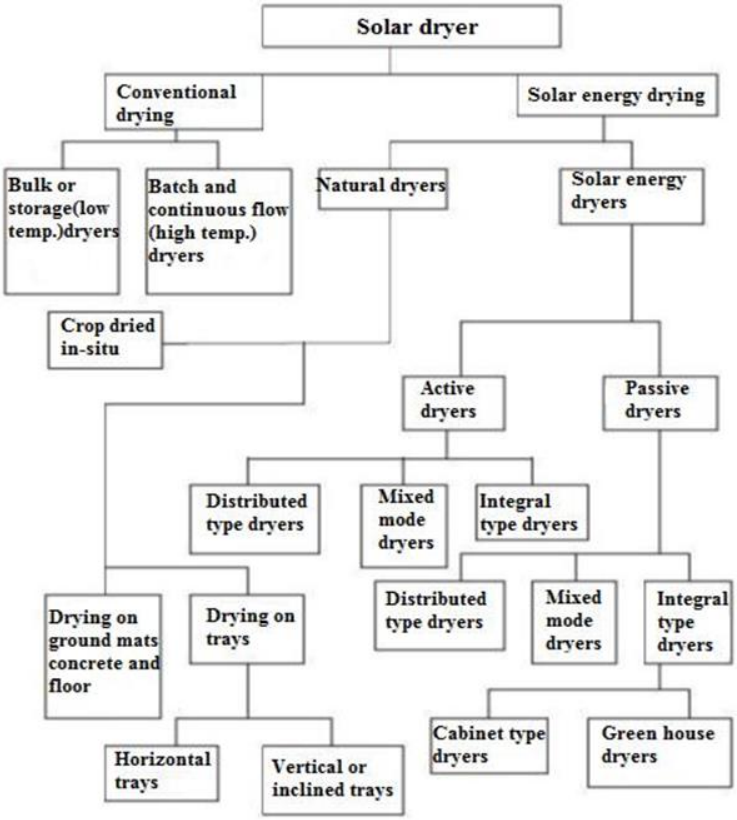

Fig.4.2. Classification of dryer and drying mode

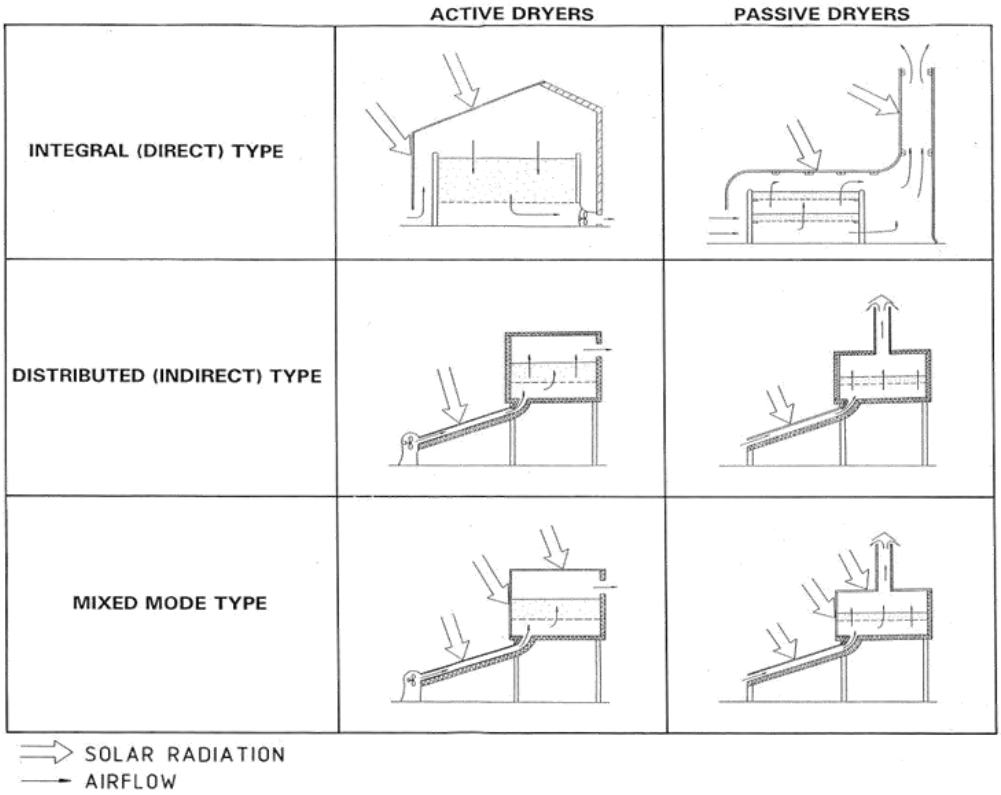

Fig.4.3. Types of Dryer

4.2.2 Methods of solar drying technologies

There are three types of solar drying technologies-

Direct Solar Drying- It is the conventional way of drying the products. In this method the products are directly exposed to the solar radiation and reduce the moisture content to atmospheric air. The air movement is due to density difference. It is broadly classified into two categories:- (1) The outdoor open air solar drying. (2) Through a transparent cover which protects partly the foodstuff from rain and other natural phenomena i.e. a passive solar drying method. This technique involves the thin layer of product spread over large space to expose to solar radiation. It is useful for grains. Material is led on outdoor floor for a long time, usually 10-30 days. It is easiest method product drying.

Indirect Solar Drying- Indirect solar drying or convective solar drying is the new technique of product drying. It is very efficient method than the direct type of solar drying. In this method the atmospheric air is heated in flat plate collector or concentrated type solar collector. The heating process is either passive or active. This hot air then flow in the cabin where products are stored. Therefore moisture from the product may lost by convection and diffusion.

Mixed Mode Solar Drying-It is combination of direct and indirect solar drying method. Product may dry with both direct exposure to solar radiation and hot air supplier on it. Air may heated in solar energy collector first then pass to the chamber where products are stored. In this process product may dry according to convective moisture loss. The same chamber is partially or totally covered with the transparent material to exposure the products to solar radiation.

Ref. [45] studied that open to the sun drying which means products are exposed directly to sun, allowed to absorbed solar radiation. It was reported that this method has many disadvantages like poor quality, contamination of product.

5. Problem statement:

Grain drying in India has been a layman process in which a loss to the grains is observed due to various weather and natural conditions. Natural or sun dried grains face a problem in storing, consuming, taste and colour. Previously, open-air sun drying has been used to dry grains, plants and other agricultural products as a means of preservation. In this method, the grains are placed on the ground or concrete floors, which can reach higher temperatures in open sun, and left there for a number of days to dry. However, large-scale production limits the use of open-air natural sun drying. It has inherent limitations like high crop losses, fungal attack, insect, birds, improper drying processes, weather uncertainties, high labour costs, large area requirement, mixing with dust, time required for drying is more, Output product quality and drying rate are poor.

Hence, there is a need to find an alternate solution which may be able to overcome all these problems. Such a solution would be using concentrated solar energy to speedily raise the temperature of grains. Also a created atmosphere of low humidity would enhance the rate of drying drastically.
method.

5.1 Drying rate curve:

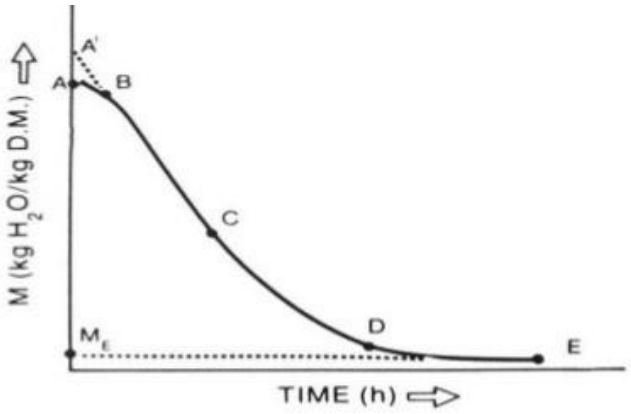

Fig.5.1. Drying rate curve with respect to moisture content and time.

AB=Settling down period, BC= Constant drying period, CD= Falling rate period, DE= Second falling rate period in fig. 5.1

For drying grains initially there is lot of moisture present. So drying is faster, uniformly it is getting dried but after sometime, amount of moisture goes down. Whatever moisture is

present inside some of those capillaries has to come up to the surface and then get dried, rate of drying will keep going down we take wet grain and leave it in an air atmosphere.

Initially it is called settling period so some drying takes place after that, for a long time the rate of drying is constant, that is called the constant drying rate period. Here, we have much moisture present the amount of moisture present at the surface is not limiting. So, the amount of heat supplied, enough for the latent heat of vaporisation, heat is good enough for the water from the liquid state to go into the gaseous state. Only that is controlling so the rate of drying is constant after some time, all the moisture on the surface is evaporated. Now, moisture from inside has to come out and then start getting evaporated. So the diffusion of this moisture which is present inside is controlling, the rate of drying goes down, this is called the falling rate period it become more and more difficult because the moisture present very much inside has to diffuse through the capillaries come out and get evaporated. so initially, constant drying rate and then after some time, the rate of drying it is falling down and down, if looking at designing dryer and we want to calculate, what should be the drying time or what will be the drying time, so the constant rate drying period and falling rate period. So, these two times need to be considered now, as the drying happens and happens, the material cannot give up moisture after some time, this moisture content is called the equilibrium moisture content. So equilibrium moisture content depends upon the percentage relative humidity so the equilibrium moisture content depends on percentage relative humidity as well as the type of material, how hydroscopic it is, how porous it is.

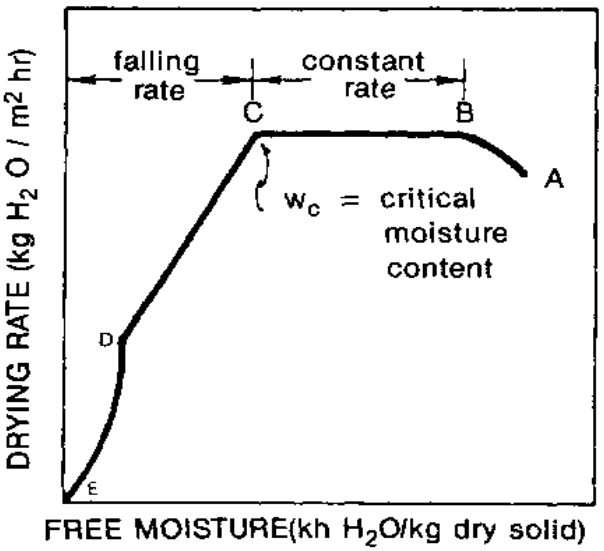

Fig.5.2. Drying rate curve with drying rate and free moisture.

This is another way to show constant rate and falling rate period. In this initially drying rate is constant. In the first falling rate, the surface drying out and drying rate fall, the second falling rate may be the surface is completely dry and moisture present indeed, capillaries starts drying out, rate of evaporation is slowly going inside the surface. So there is a zone of evaporation taking place, it becomes difficult for the moisture present in the capillaries to get evaporated. In the falling rate period, the rate of drying is influenced by the rate of movement of moisture within the solid and the influence of air velocity decreases ,the air velocity, which is contributing to the drying decreases, it is only the diffusion, the amount of moisture removed in the falling rate may be very small but generally, the falling rates are very, very large. So, it is the constant rate may be only say few minutes but the falling rate period could be several hours as well so we need to consider both to designing a dryer.

6. Scope of the work:

Drying techniques are well developed as evident from published papers and articles on the topic. As above we have discussed various types of dryer have been developed as shown in Fig 4.3.

Present research focuses on drying with desiccant material. The system under study comprising of, desiccant wheel and dryer will use solar energy for heating purposes. Although, different dryers has been developed in various countries, but enough attention has not been given in India. By using various techniques, the drying process in India, can be evaluated which will further help in reduction of cost and improvement in efficiency of dried grains.

A major objective of the research is to design and develop the desiccant based grain dryer and methods for drying. Another major objective is to improve the drying rate of grains under low-temperature conditions in which the driving force for mass transfer can be enhanced by several strategies. Reducing the relative humidity of hot air is one such approach, which increases the moisture-absorbing capacity of drying air. This helps in maintaining higher driving force for mass transfer between inner layers and the material surface. The desiccant based drying system can be used for drying of grains and reduce drying time and improve quality of the dried product. So, to solve the problem of uncontrolled drying temperature and unfavourable climatic conditions there is a need to develop a desiccant based food drying system in which a dehumidifier is used to absorb the moisture from air and with the help of heater, air is dried to desirable relative

humidity and temperature and passed through grains in drying chamber. Temperature of drying air and airflow rate are crucial parameters for increasing the drying rate and dried grain quality and hence needs to be optimized for drying of grains in a desiccant based drying system which is some important targets of this research.

7. Objectives:

On the basis of literature review, following are the proposed objectives of the research work to be done during the Ph.D. program.

1) Evaluation of a desiccant dehumidifier for grain drying.
2) Design and Development of desiccant based dryer.
3) A detailed chart will be prepared, depicting the drying procedure for desiccant based drying system.

The advantages associated with the proposed grain dryer are:

- Moderate capacity dryer with a low cost.
- Faster drying rate: drying rate is high as compare to direct solar drying.
- Good quality of dried grain
- Losses in product are avoided on the circumstances of natural phenomena.

The dried grain using the proposed grain drier will have high nutritious value as compared to direct drying due to safe and control environment.

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